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**F-K ANALYSIS OF ARRAY AND SINGLE-STATION DATA
TO IDENTIFY SOURCES OF NEAR-RECEIVER AND
NEAR-SOURCE SCATTERING**

I. N. Gupta
C. S. Lynnes
T. W. McElfresh
R. A. Wagner

Teledyne Geotech Alexandria Laboratory
314 Montgomery Street
Alexandria, VA 22314-1581

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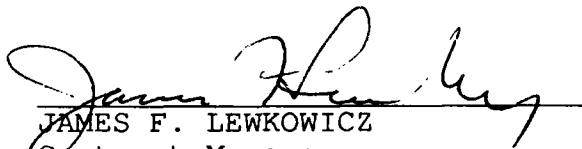
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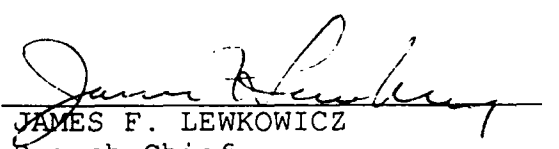
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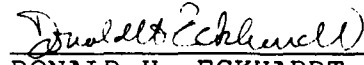
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JAMES F. LEWKOWICZ
Contract Manager
Solid Earth Geophysics Branch
Earth Sciences Division


JAMES F. LEWKOWICZ
Branch Chief
Solid Earth Geophysics Branch
Earth Sciences Division

FOR THE COMMANDER


DONALD H. ECKHARDT, Director
Earth Sciences Division

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<p style="text-align: center;">SECTION A</p> <p>F-k analyses of short-period recordings of both U.S. and Soviet underground nuclear explosions at the Eskdalemuir (EKA). Scotland array indicate arrivals from a local source about 15 km due north-west of the array. Use of residual seismograms derived by subtracting the beamed record from each array channel confirmed the presence of the same scatterer. The secondary seismic source appears to be short-period surface waves due to the scattering of incident P waves at a nearby deep valley known as Moffat Water, in agreement with Key's (1967) earlier results. Similar analyses of the NORESS (Norway) array data from U.S. and Soviet nuclear shots also indicate secondary arrivals suggesting a local near-surface scatterer about 25-30 km south-west of the array, in the region of Lake Mjosa. Thus, short-aperture array data can be useful in identifying and locating sources of near-receiver scattering.</p>					
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SECTION B

F-k analyses of short-period recordings of both explosion and earthquake sources at the high-frequency NORESS array indicate secondary arrivals from a near-receiver source about 25-30 km southwest of the array. Use of residual seismograms, derived by subtracting the beamed record from each array channel, improved the identification of the same scatterer. F-k power difference plots, obtained by subtracting (after normalization) the f-k power versus slowness estimates for the initial *P* window from those for the later windows, provided nearly identical results. The secondary seismic source appears to be short-period surface waves, *Rg*, generated by the scattering of incident *P* waves in the region of Lake Mjosa, 27 km SW of NORESS, where there is about 1 km of relief from the bottom of the lake to the top of an adjacent hill. Polarization analyses of two explosions recorded on three-component elements of NORESS also suggested a secondary phase with polarization characteristic of *Rg* and arrival time and azimuth consistent with those derived from the f-k analyses for one but not for the other shot. Near-source scattering is investigated by f-k analysis of data from reciprocal arrays formed by interchanging the roles of source and receiver. Application to closely spaced Yucca Flat (NTS) shots recorded at several stations provides evidence for *Rg* → *P* scattering near the northwestern and other basin boundaries of the Yucca Valley. It seems that deterministic locations of near-receiver *P* → *Rg* and near-source *Rg* → *P* scattering can be obtained by f-k techniques.

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SUMMARY

SECTION A

F-k analyses of short-period recordings of both U.S. and Soviet underground nuclear explosions at the Eskdalemuir (EKA), Scotland array indicate arrivals from a local source about 15 km due north-west of the array. Use of residual seismograms derived by subtracting the beamed record from each array channel confirmed the presence of the same scatterer. The secondary seismic source appears to be short-period surface waves due to the scattering of incident P waves at a nearby deep valley known as Moffat Water, in agreement with Key's (1967) earlier results. Similar analyses of the NORESS (Norway) array data from U.S. and Soviet nuclear shots also indicate secondary arrivals suggesting a local near-surface scatterer about 25-30 km south-west of the array, in the region of Lake Mjosa. Thus, short-aperture array data can be useful in identifying and locating sources of near-receiver scattering.

SECTION B

F-k analyses of short-period recordings of both explosion and earthquake sources at the high-frequency NORESS array indicate secondary arrivals from a near-receiver source about 25-30 km southwest of the array. Use of residual seismograms, derived by subtracting the beamed record from each array channel, improved the identification of the same scatterer. F-k power difference plots, obtained by subtracting (after normalization) the f-k power versus slowness estimates for the initial P window from those for the later windows, provided nearly identical results. The secondary seismic source appears to be short-period surface waves, Rg, generated by the scattering of incident P waves in the region of Lake Mjosa, 27 km SW of NORESS, where there is about 1 km of relief from the bottom of the lake to the top of an adjacent hill. Polarization analyses of two explosions recorded on three-component elements of NORESS also suggested a secondary phase with polarization characteristic of Rg and arrival time and azimuth consistent with those derived from the f-k analyses for one but not for the other shot. Near-source scattering is investigated by f-k analysis of data from reciprocal

arrays formed by interchanging the roles of source and receiver. Application to closely spaced Yucca Flat (NTS) shots recorded at several stations provides evidence for $Rg \rightarrow P$ scattering near the northwestern and other basin boundaries of the Yucca Valley. It seems that deterministic locations of near-receiver $P \rightarrow Rg$ and near-source $Rg \rightarrow P$ scattering can be obtained by f-k techniques.

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SECTION A

GEOPHYSICAL RESEARCH LETTERS, VOL. 17, NO. 2, PAGES 183-186, FEBRUARY 1990

BROADBAND F-K ANALYSIS OF ARRAY DATA TO IDENTIFY SOURCES OF LOCAL SCATTERING

I. N. Gupta, C. S. Lynnes, and R. A. Wagner

Teledyne Geotech, Alexandria, Virginia

Abstract. F-k analyses of short-period recordings of both U.S. and Soviet underground nuclear explosions at the Eskdalemuir (EKA), Scotland array indicate arrivals from a local source about 15 km due northwest of the array. Use of residual seismograms derived by subtracting the beamed record from each array channel confirmed the presence of the same scatterer. The secondary seismic source appears to be short-period surface waves due to the scattering of incident P waves at a nearby deep valley known as Moffat Water, in agreement with Key's (1967) results. Similar analyses of the NORESS (Norway) array data from U.S. and Soviet nuclear shots also indicate secondary arrivals suggesting a local near-surface scatterer about 25-30 km southwest of the array, in the region of Lake Mjosa. Thus, short-aperture array data can be useful in identifying and locating sources of near-receiver scattering.

Introduction

There have been few studies of teleseismic P coda in which actual sources of scattering have been identified. Perhaps the most convincing study so far has been the identification of scattered arrivals from the region of a narrow lake in Scotland, about 13 km long called Moffat Water which lies at the bottom of a northeast-southwest trending 200 m deep valley (Key, 1967). By beaming Eskdalemuir (EKA) array records from several earthquakes and nuclear explosions, Key identified a low-frequency, Rayleigh wave arrival with velocity of about 2.5 km/sec from the direction 315°, originating about 13 km from the center seismometer. Theoretical studies by Hudson and Boore (1980) confirmed the source of the local wave to be due to scattering of incident P into Rayleigh waves. In this study, we demonstrate the usefulness of broadband f-k analysis to identify sources of local scattering such as Moffat Water near EKA and Lake Mjosa southwest of the small-aperture NORESS array. Both U.S. and Soviet nuclear explosions are used as seismic sources to provide different source-receiver azimuths. Residual seismograms formed by subtracting the array beam from each channel improve identification of the sources of locally scattered arrivals.

F-K Analysis of U.S. and U.S.S.R. Shots at EKA

Array recordings of seismic events are useful for studying detailed characteristics of wave propagation across the array. We use a broadband f-k technique described by Kvaerna and Ringdal (1986)

The method was first applied to the Eskdalemuir (EKA) array recordings of two underground nuclear explosions. The EKA array has 20 elements arranged in an "L" configuration with element spacing of 0.9 km and maximum element spacing of 9.8 km (Bache et al., 1985). The results are expressed in terms of frequency-slowness spectral estimates of the signal at specified times. Starting a few seconds before the onset of P, Parzen-tapered 6.4 sec long windows, with incremental shifts of 0.2 sec, were used to obtain the frequency-slowness plots. A single element record of the Nevada Test Site (NTS) shot, KASSERI (28 October 1975, $m_b = 6.2$, epicentral distance, $\Delta = 72^\circ$, back-azimuth 309°) is shown in Figure 1a. The results of f-k analysis for several time windows are shown in Figure 2. Here the P window is defined as that centered on the onset of P so that it contains only 3.2 sec of signal. The window starting 1 sec after the P window (designated the P+1 sec window) was generally found to have the highest power and may therefore be considered to represent the initial P. On each slowness plot, the highest amplitude value is indicated (with power in db) along with its direction of approach or back-azimuth (in degrees) and phase velocity (in km/sec). The contour interval is 1 db and a range of 10 db is used. The signal/noise ratio for the EKA recordings of KASSERI is good over the frequency range of 0.5 to 3.0 Hz. The corresponding broadband results for the P+1 sec and P+5 sec windows are shown in Figures 2a and 2b, respectively. Figure 2c shows results for the narrow frequency passband of 1 ± 0.25 Hz. Dominant energy in the first window shows a back-azimuth of 305° and phase velocity of about 19 km/sec; both are close to the expected values for initial P. The power contours are, as expected, elongated along directions that coincide with the directions of the two arms of the EKA array. In addition to main arrivals from the explosion source region, Figures 2b-c suggest low-phase-velocity, secondary sources of energy, especially from the northwest direction, probably due to forward-scattering of teleseismic P to surface waves, as suggested by Key's (1967) observations.

In order to enhance the local secondary arrivals with respect to the primary arrival, residual P and P coda were obtained by subtracting the time-domain beam from the original P waveform for each EKA channel. The beam used for this purpose was obtained by aligning the first peaks after the onset of P and summing all channels. The resulting residual seismograms, expected to be richer in near-receiver effects since the principal arrival due to direct P has been suppressed, were then used to obtain the frequency-slowness plots. Results for the P+5 sec window but for three different frequency passbands (Figures 2d-f) indicate a consistent, low phase velocity principal arrival. A comparison of Figures 2b-c with 2d-e demonstrates the usefulness of residual seismograms in the identification and location of sources of near-receiver scattering.

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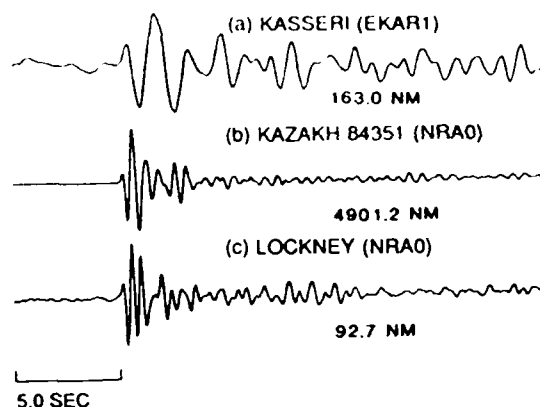


Fig. 1. Single element records of (a) KASSERI at EKA array and (b) Kazakh shot of 16 December 1984 and (c) LOCKNEY at NORESS array. Zero-to-peak amplitudes are given in nanometers.

The maximum amplitude arrivals in Figures 2d-f indicate a phase velocity of about 3 km/sec and back-azimuth of about 310° . Combining this with the phase velocity and back-azimuth in Figure 2a and assuming the scattering takes place near the surface, the scatterer should lie about 15 km from the center element of the array. These results agree remarkably well with those of Key (1967). For a center frequency of 2 Hz (Figure 2f), the distribution of

secondary arrivals appears to be almost random, with many sources of nearly equal amplitudes. It is interesting to note that Key (1967) found the spectrum of the local wave to peak around 1 Hz and drop sharply at higher frequencies.

A similar analysis was applied to EKA array records of Eastern Kazakh shot of 23 December 1979 ($m_b = 6.2$, $\Delta = 47^\circ$, back-azimuth 61°). The most prominent secondary arrival appears in the P+7 sec windows, with nearly the same direction and phase velocity as that for the U.S. shot. This arrival time is later than those in Figures 2b-e, which is consistent with the longer travel path of the scattered incident P wave relative to the direct P. Assuming near-surface scattering, these results indicate the scattering source to be about 15 km from the array center, in the vicinity of Moffat Water, again in agreement with Key's results.

F-K Analysis of U.S. and U.S.S.R. Shots at NORESS

We now show results from similar analysis of data from the short-aperture array, NORESS, which consists of sensors within a 3 km diameter array (Ingate et al., 1985). The 24 short-period vertical-component sensors used in this study are located along four concentric rings. A single element record of the Eastern Kazakh shot of 16 December 1984 ($m_b = 6.1$, $\Delta = 38^\circ$, back-azimuth 75°) is shown in Figure 1b. A shorter (3.2 sec long) window is used for f-k analysis because of the smaller dimensions of NORESS as compared to EKA. Results are shown in Figure 3 in which the initial P window indicates the largest-amplitude arrival

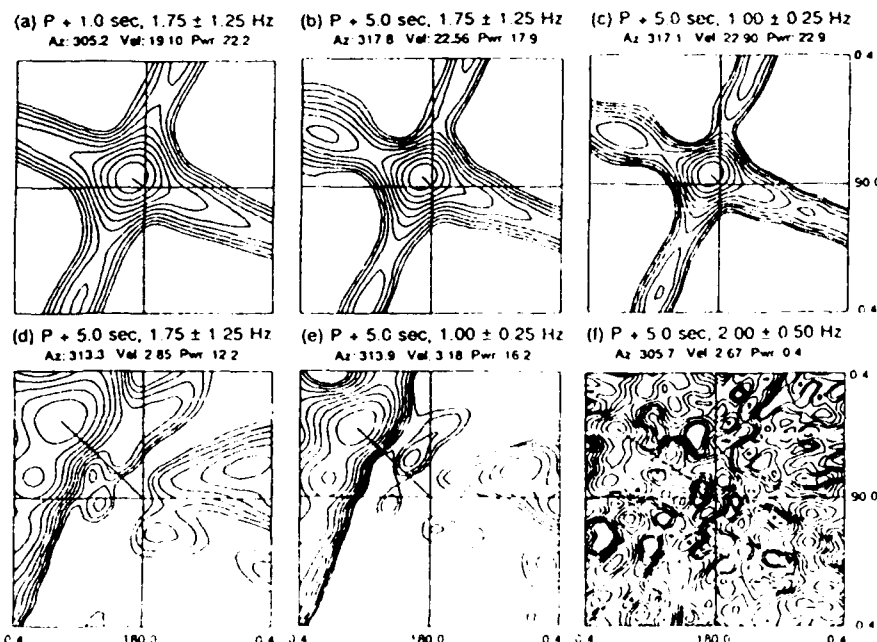


Fig. 2. Frequency-slowness spectral estimates derived from (a c) normal and (d f) residual EKA records of KASSERI. The numbers on top of each plot indicate back-azimuth (deg), phase velocity (km/sec), and signal power (dB), respectively of the highest-amplitude arrival which is shown connected to the origin. The maximum slowness value is 0.4 sec/km. The signal windows and frequency passbands are indicated on each plot. Note the low phase velocity arrival from the northwest direction appearing as a secondary arrival in plots (b) and (c), and as the principal arrival in plots (d f).

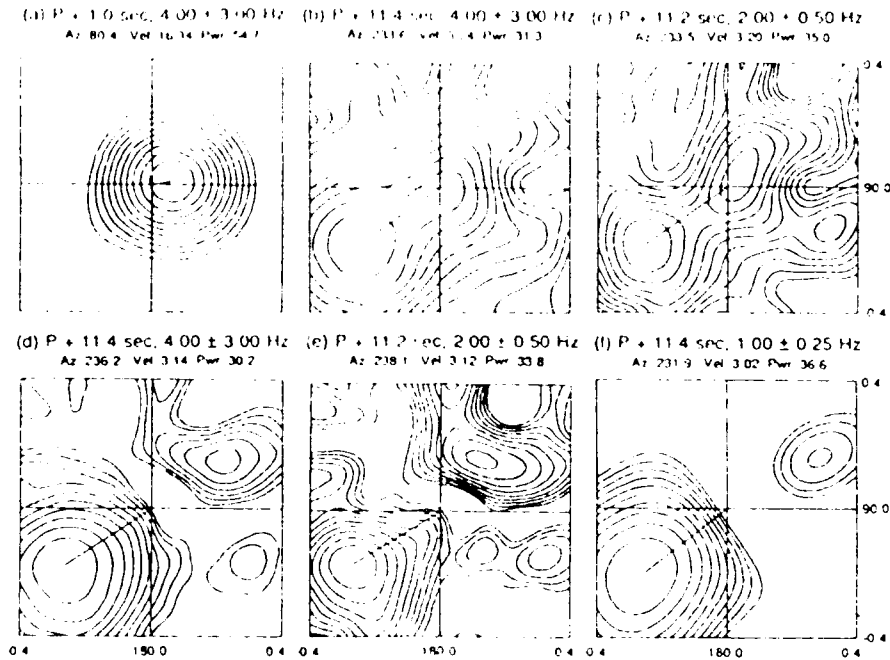


Fig. 3. Similar to Fig. 2 but derived from NORESS records of the Kazakh shot of 16 December 1984. A low phase velocity arrival from the southwest direction appears as the principal phase on all five later arrival windows.

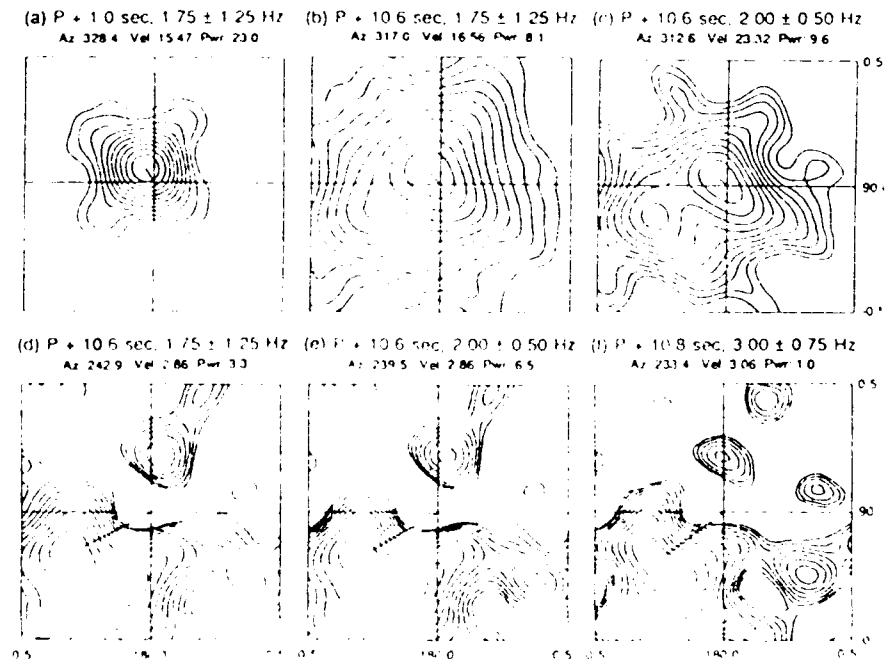


Fig. 4. Similar to Fig. 2 derived from NORESS records of LOCKNEY except that the maximum slowness is 0.5 sec/km. The low phase velocity arrival from the southwest direction is hardly seen in (b), appears as a secondary arrival in (c) but appears as the principal arrival in plots (d-f).

to have a back azimuth of 80° (Figure 3a), in good agreement with the expected value. Two later windows with frequency passbands of 4 ± 3 Hz and 2 ± 0.5 (Figures 3b-c) indicate prominent secondary arrivals from the southwest direction. Figures 3d-f show the residual seismogram f-k results for passbands of 4 ± 3 Hz, 1 ± 0.25 Hz, and 2 ± 0.5 Hz. Each of these figures indicate low-phase-velocity arrivals from the southwest. A comparison of Figures 3d-e with 3b-c shows that the use of residual seismograms again facilitates the isolation of secondary sources. Assuming the secondary source to be near the surface, the results in Figure 3 suggest the scatterer to be 25-30 km from the array. It is interesting to note that there is a large lake (Lake Mjosa), trending northwest-southeast, about 24 km southwest of NORESS. There is steep topography surrounding the lake in this direction; the hills immediately to the west of the lake have an elevation of 600 m above the lake, which is approximately 400 m deep, producing total relief of 1000 m over a short horizontal distance. It seems likely that the scatterer is associated with this prominent feature.

Frequency-slowness plots derived from NORESS records of the NTS shot, LOCKNEY (24 September 1987, $m_b = 5.7$, $\Delta \approx 74^\circ$, back-azimuth 319°) are shown in Figure 4. The results are similar to those in Figure 3, indicating nearly the same azimuthal direction for the scatterer. The scattered arrivals in plots derived from residual seismograms (Figures 4d-f) are significantly more prominent than those from normal seismograms (Figures 4b-c). Again the results in Figure 4 suggest the source of scattering to be about 25-30 km from the array.

Conclusions

F-k spectral analyses of short-period data from the EKA and NORESS arrays have been used to identify and locate sources of local scattering. Residual seismograms have been found to be useful in isolating the secondary source from the effects of the primary source. Using both U.S. and U.S.S.R. nuclear explosions as the seismic sources, the scattered arrivals have been identified as low-velocity

Rayleigh waves originating from the deep valley, Moffat Water near EKA and the vicinity of Lake Mjosa near NORESS.

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I. Gupta, C. Lynnes, and R. Wagner, Teledyne Geotech, 314 Montgomery, Alexandria, VA 22314.

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SECTION B INTRODUCTION

Few studies of teleseismic P arrivals have been successful in identifying and locating actual sources of scattering. One of the most convincing analyses has been the identification of scattered arrivals from the region of Moffat Water, a narrow lake in Scotland about 8 miles long, which lies at the bottom of a 600 ft deep valley (Key, 1967, 1968). The valley lies in a NE-SW direction, and the apparent secondary source is at a point about one third of its length from the northeastern end, where it cuts through a basalt and dolerite dyke. By beaming Eskdalemuir (EKA) array records from several earthquakes and nuclear explosions, Key identified a low-frequency Rayleigh-wave arrival with velocity of about 2.5 km/sec from the direction 315° and originating at a distance of about 13 km from the center seismometer. The direction and velocity of the local wave did not change in spite of variation in source azimuthal direction of over 50° , suggesting it to be due to a relatively small localized heterogeneity. Particle-motion analysis of three-component data confirmed the local wave, with an amplitude generally about 20% to 40% of that of the incident P wave, to have the character of a Rayleigh wave. Theoretical studies by Hudson (1967) and Hudson and Boore (1980) also indicated the source of the local wave to be due to scattering of incident P into Rayleigh wave. Broadband f - k analysis of EKA recordings of both U.S. and Soviet nuclear explosions further confirmed the secondary seismic source to be from Moffat Water (Gupta *et al.*, 1990). Residual seismograms obtained by subtracting the beamed record from each array channel significantly improved identification of the sources of locally scattered arrivals.

Our recent f - k analyses of data from the high-frequency seismic array NORESS (Norway) suggested the presence of a local scatterer about 25-30 km southwest of the array, in the

region of Lake Mjosa (Gupta *et al.*, 1989; Gupta *et al.*, 1990). In this more detailed study, Soviet and U.S. nuclear explosions and an earthquake are used as the seismic sources, providing significantly different source-receiver azimuthal directions. Two new f-k techniques based on the use of residual seismograms and f-k power difference plots help improve identification of the scatterer. Similar results are obtained by polarization analysis of three-component NORESS data.

In simple terms, the principle of reciprocity means that the source and receiver positions in a seismic experiment can be exchanged without affecting the observed seismograms. Consequently, single observation point records of closely spaced seismic sources can be used to form an array on which conventional array processing techniques can be applied (Spudich and Bostwick, 1987). Teleseismic *P* arrivals from Yucca Flat explosions are known to have complex waveforms that vary considerably from one shot to another. Finite-difference simulations have explained much of this complexity as being due to the scattering of explosion-generated Rayleigh waves into teleseismic body waves because of laterally varying structure (McLaughlin *et al.*, 1987; Stead and Helmberger, 1988). An attempt is made here to examine near-source scattering for Yucca Flat shots by f-k analysis of data from several stations by forming reciprocal arrays. The results are interpreted on the basis of the known geology of the Yucca Flat test site. Both near-receiver and near-source scattering play important roles in the monitoring of underground nuclear tests. For example, the Lg phase from explosions, known to be strongly influenced by scattering (e.g., Gupta and Blandford, 1983), is often used for the detection, source discrimination, and yield determination of underground nuclear explosions.

F-K AND POLARIZATION ANALYSIS OF USSR AND U.S. SHOTS AT NORESS

Array recordings of seismic events are useful for studying detailed characteristics of wave propagation across the array. Broadband f-k methods have been used to detect various seismic arrivals and determine their phase velocity and azimuth (Kvaerna and Doornbos, 1986; Kvaerna, 1989; Ringdal and Kvaerna, 1989). The f-k technique used here is described by Kvaerna and Doornbos (1986) and Kvaerna and Ringdal (1986).

We first applied the broadband f-k spectra method to the NORESS recordings of two underground nuclear explosions. The NORESS small-aperture array consists of sensors within a 3 km diameter, and the 24 short-period vertical-component sensors used in this study are located along four concentric rings (Kvaerna, 1989). The results are expressed in terms of frequency-slowness spectral estimates of the signal along various azimuthal directions. Starting a few seconds before the onset of P , Parzen-tapered 3.2 sec (128 point) windows, with incremental shift of 0.2 sec, were used to obtain the frequency-slowness plots. Results from the Kazakh shot of 16 December 1984 ($m_b = 6.1$, $\Delta \approx 38^\circ$, back-azimuth 75°) are shown in Figure 1. Here the P window is centered on the onset of P so that it contains only 1.6 sec of signal. The window starting 1 sec after the P window (designated the $P + 1$ sec window) was generally found to have the highest power and may therefore be considered to represent the initial P . On each slowness plot, the highest amplitude value is indicated (with power in db) along with its direction of approach or back-azimuth (in degrees) and phase velocity (in km/sec). The contour interval is 1 db, and a range of 10 db is used. The signal/noise ratio for the NORESS recordings of this explosion is good over the frequency range of about 0.5 to 7.0 Hz. The broadband (1 to 7 Hz) results for the $P + 1$ sec and $P + 11.4$ sec windows are

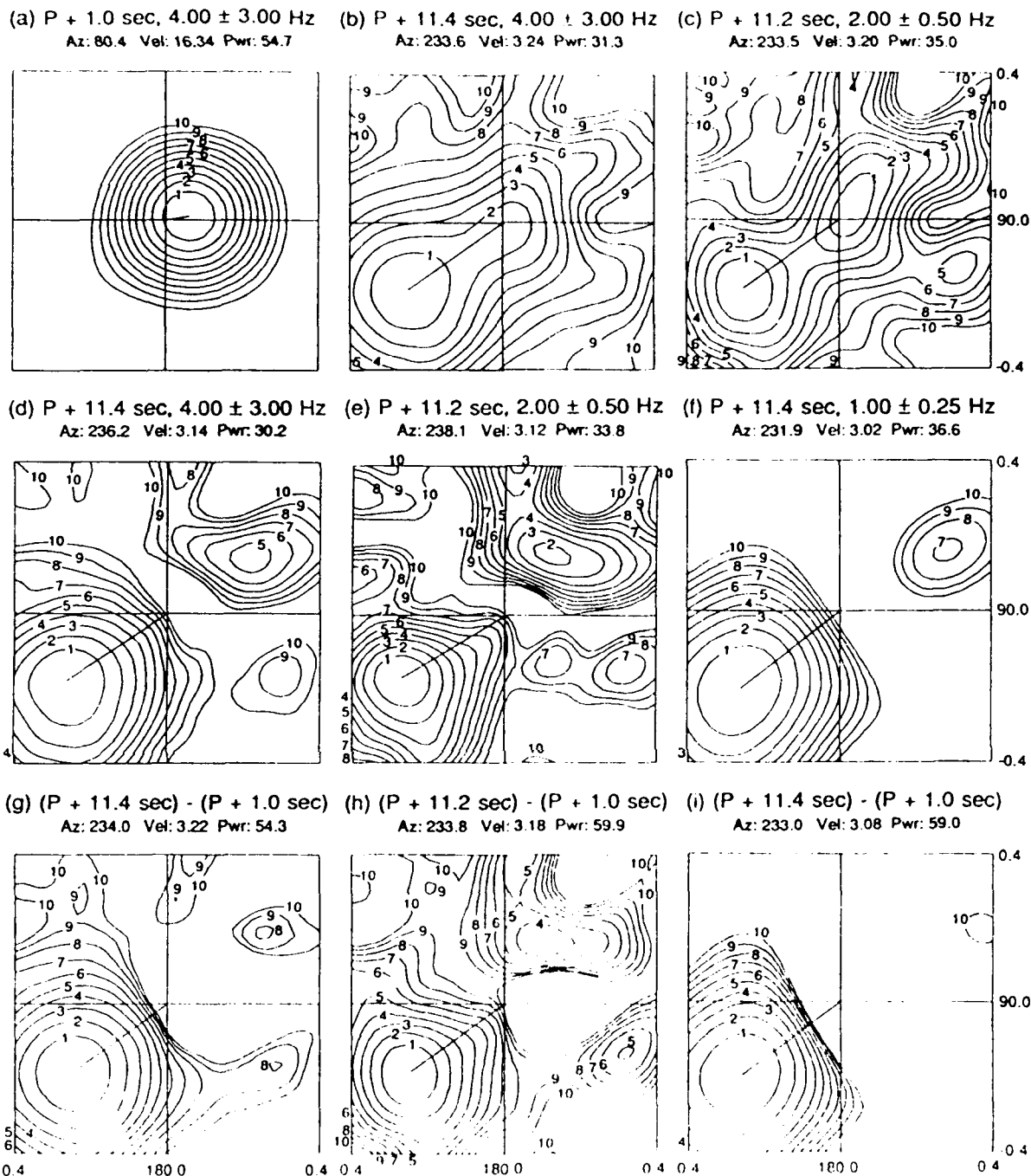


Figure 1. Frequency-slowness spectral estimates derived from NORESS records of the Kazakh shot of 16 December 1984 based on the use of (a, b, c) normal, (d, e, f) residual seismograms, and (g, h, i) f-k power difference plots. The numbers on top of each plot indicate back-azimuth (deg), phase velocity (km/sec), and signal power (dB), respectively of the highest-amplitude arrival which is shown connected to the plot origin. The maximum slowness value is 0.4 sec/km. The signal windows and frequency passbands are indicated on each plot. Note the low phase velocity arrival from the southwest direction appearing as the principal phase on all eight later arrival windows.

shown in Figures 1a and 1b, respectively. Figure 1c shows results for the narrow frequency passband of 2.0 ± 0.5 Hz. Dominant energy in the first window shows a back-azimuth of about 80° and phase velocity of about 16 km/sec; both are close to the expected values for initial P . In addition to main arrivals from the explosion source region, Figures 1b and 1c suggest low-phase-velocity secondary sources of energy, especially from the southwest direction.

The local secondary arrivals were enhanced with respect to the primary arrival by subtracting the time-domain beam from the original P waveform for each array channel and using the resulting residual seismograms for f - k analysis (Gupta *et al.*, 1990). This simple but effective method constitutes a first step in iterative beamforming of two simultaneous signals and provides a first approximation to a maximum likelihood estimate (Blandford *et al.*, 1976). Results for the same two windows and frequency passbands as in Figures 1b and 1c are shown in Figures 1d and 1e, respectively; a comparison clearly demonstrates the usefulness of residual seismograms in the identification and location of sources of near-receiver scattering. Figure 1f shows results, based on the use of residual seismograms, for the lower frequency passband of 1.00 ± 0.25 Hz. The three Figures 1d, 1e, and 1f consistently indicate a prominent low phase velocity arrival from nearly the same azimuthal direction.

An attempt was also made to investigate secondary sources of scattering with the help of f - k power difference plots obtained by subtracting the normalized two-dimensional matrix of f - k power versus slowness estimates of the initial P window from those for the later windows. Results for the same three frequency passbands as used in Figures 1d, 1e, and 1f are shown in Figures 1g, 1h, and 1i, respectively. The three figures indicate the same prominent low phase velocity arrival from nearly the same azimuth. It appears therefore that f - k power

difference plots provide another simple and effective method for studying the characteristics of secondary arrivals.

The maximum amplitude arrivals in all eight figures based on later time windows (Figures 1b through 1i) indicate a phase velocity of about 3 km/sec and back-azimuth of about 235° . Combining this with the phase velocity and back-azimuth in Figure 1a and assuming the scattering to take place near the surface, the scatterer should lie 25-30 km from the array. There is a large lake, Lake Mjosa, running along the northwest to southeast direction, about 24 km southwest of NORESS. The hills immediately to the west of the lake have an elevation of 600 m above the lake, which is approximately 400 m deep, meaning that there is a variation in elevation from the bottom of the lake to the top of the hill of 1000 m over a short horizontal distance (S. Mykkeltveit, personal communication, 1989). It seems likely that the scatterer is associated with this prominent geological feature which has the largest topographical relief within at least 50 km of the array.

Frequency-slowness plots derived from NORESS records of the NTS shot LOCKNEY (24 September 1987, $m_b = 5.7$, $\Delta \approx 74^\circ$, back-azimuth 319°) are shown in Figure 2, which includes results from normal f-k analysis (Figures 2a, 2b, and 2c), from residual seismograms (Figures 2d, 2e, and 2f), and from f-k power difference plots (Figures 2g, 2h, and 2i). Results are similar to those in Figure 1, indicating nearly the same azimuthal direction for the scatterer. The secondary arrival is most prominent in the $P + 10.6$ sec window. The earlier arrival time, as compared to those in Figures 1b through 1i, is consistent with the somewhat shorter travel path of the scattered incident P wave relative to the direct P . The scattered arrivals in plots derived from residual seismograms (Figures 2d, 2e, and 2f) as well as those from difference f-k plots (Figures 2g, 2h, and 2i) are significantly more prominent than those

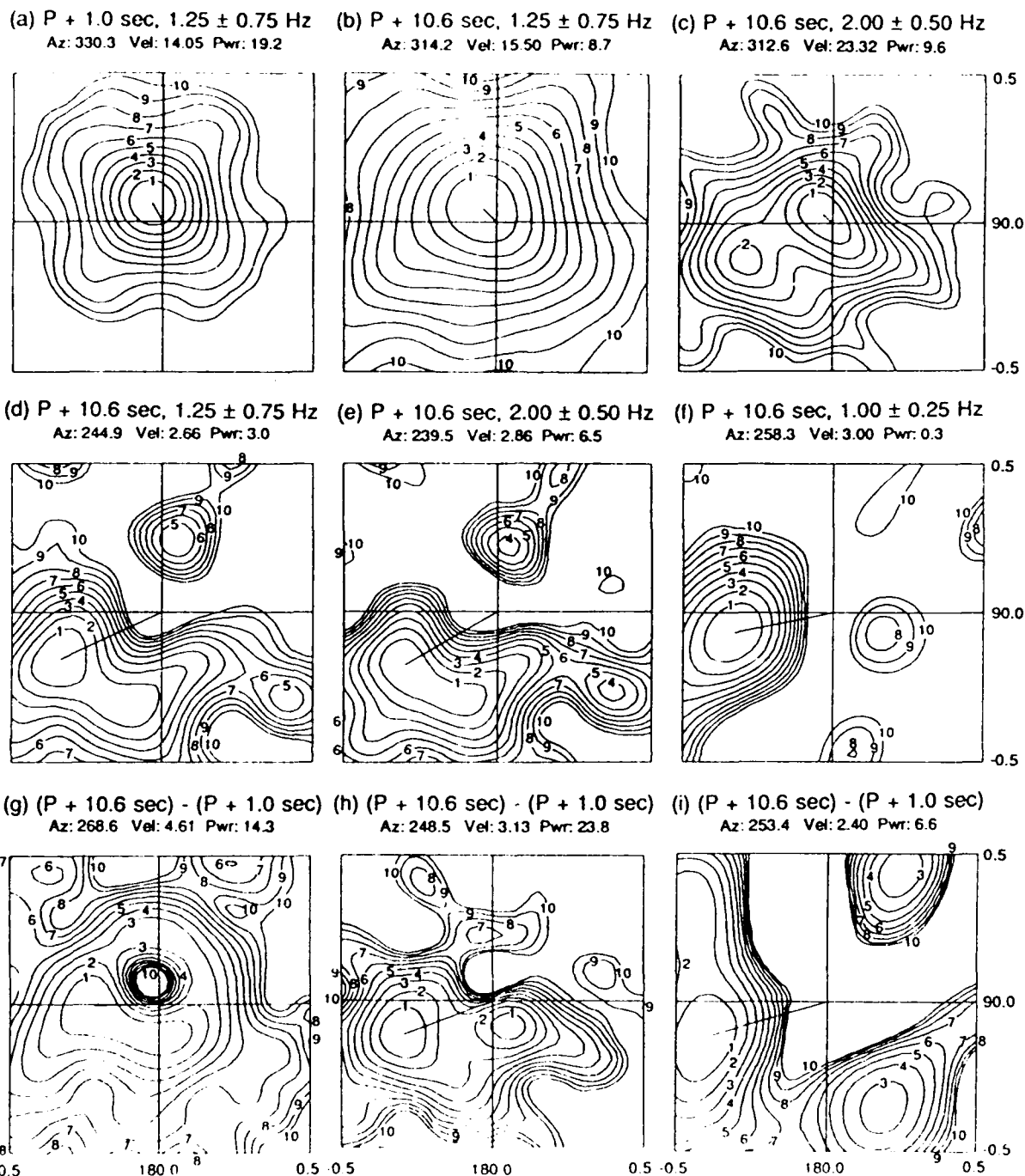


Figure 2. Similar to Figure 1 but derived from NORESS records of LOCKNEY with a maximum slowness of 0.5 sec/km. The low phase velocity arrival from the southwest direction is hardly seen in (b), appears as a secondary arrival in (c) but appears as the principal phase in nearly all other later arrival windows.

from normal seismograms (Figures 2b and 2c). Again the results in Figure 2 suggest the source of scattering to be about 25-30 km from the array.

Polarization analyses of the four 3-component short-period elements of NORESS for the USSR and U.S. explosions described earlier were carried out using the method of Jurkevics (1988). A zero-phase Butterworth bandpass filter is applied to the data, and covariance matrices are averaged over the array for a sliding window. The polarization ellipsoid, representing the best fit to the data in a least-squares sense, is computed from the average covariance matrix. The characteristics of ground motion can be specified in terms of attributes derived from the principal axes of the polarization ellipsoid. Denoting the latter by λ_1 , λ_2 , and λ_3 , where $\lambda_1 \geq \lambda_2 \geq \lambda_3$, the degree of rectilinearity is given by $(1 - (\lambda_2 + \lambda_3)/2\lambda_1)$ which is 1.0 when there is only one nonzero eigenvalue, as for pure P waves. Pure Rayleigh-wave motion is elliptical and the particle motion is confined to a plane. Defining oblateness as $2(\lambda_2 - \lambda_3)(\lambda_1 - \lambda_3)/(\lambda_1^2 + \lambda_2^2 + \lambda_3^2)$, Rayleigh waves should be characterized by very oblate (i.e., flat elliptical) polarization (the maximum oblateness is 1, when $\lambda_1 = \lambda_2$ and $\lambda_3 = 0$). Results from the Kazakh shot, based on the 0.5-1.0 Hz band, are shown in Figure 3, indicating a prominent phase with a polarization characteristic of Rayleigh waves arriving about 11 sec after P . The back-azimuth computed from the polarization is about 220-250°. The arrival time and azimuth are therefore consistent with those for the secondary seismic source in the f - k analyses (Figure 1). Similar analysis was carried out for the NTS shot LOCKNEY (Figure 4). The rectilinearity is generally high, indicating predominantly P -wave motion, probably representing teleseismic P waves from the source region. This is supported by the f - k analyses in Figures 2b and 2c, which indicate a large amount of energy arriving from the source region several seconds after the direct P . Rayleigh wave motion is not apparent in the

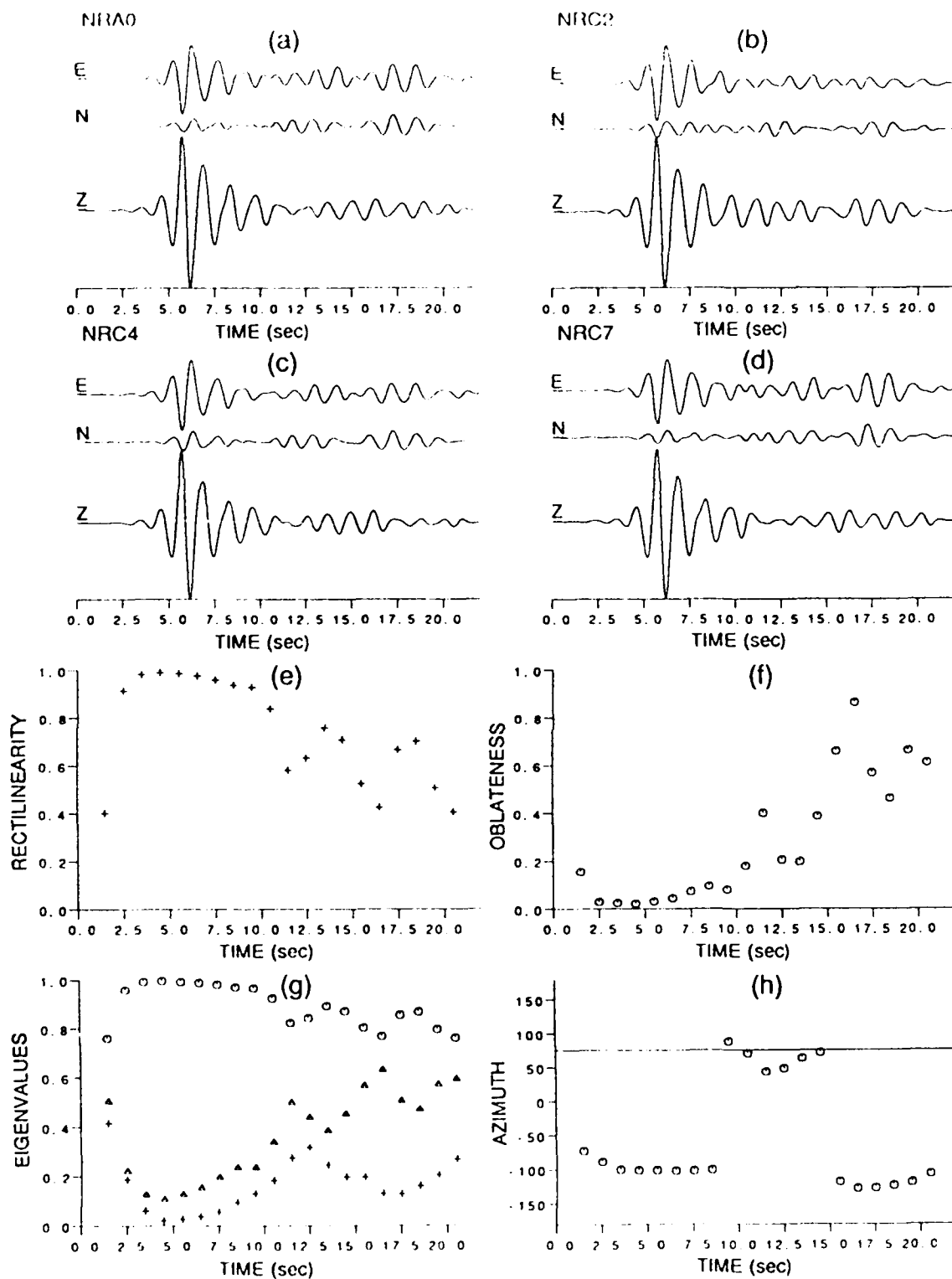


Figure 3. Polarization analysis of 16 Dec 1984 Shagan River event. (a, b, c, d) Three-component NORESS seismograms. (e) Rectilinearity versus time. (f) Oblateness versus time. (g) Eigenvalue amplitudes (normalized to 1). (h) Back-azimuth, assuming Rayleigh wave polarization; line shows back-azimuth to Shagan River.

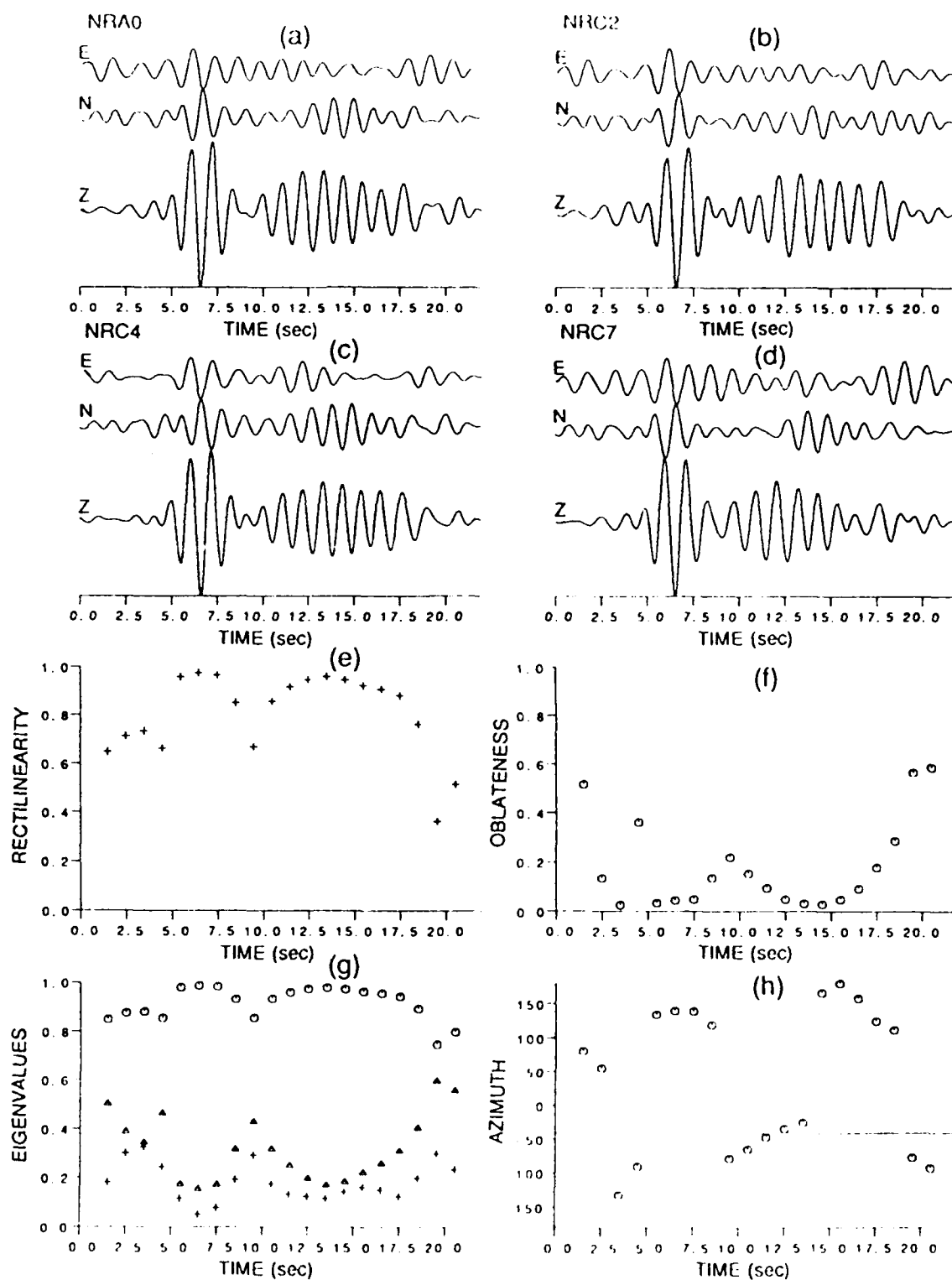


Figure 4. Similar to Figure 3 for the NTS shot, LOCKNEY.

polarization until about 14 seconds after the direct P. The back-azimuth is $260-280^\circ$, in rough agreement with the f-k results.

F-K ANALYSIS OF AN INTERMEDIATE-FOCUS EARTHQUAKE AT NORESS

We carried out f-k analysis on NORESS data from an earthquake in Romania (45.82° N, 26.65° E, August 1, 1985, $m_b = 4.7$, depth 122 km, $\Delta \approx 17^\circ$, back-azimuth 142°) in order to examine any possible influence of variations in source-type and source-receiver azimuth on the determination of near-receiver scattering. The results are shown in Figure 5. The $P + 1$ sec window (Figure 5a) indicates the expected phase velocity and back-azimuth, whereas the two $P + 11.6$ sec windows (Figures 5b, c) contain some evidence of a low-phase-velocity secondary arrival from the southwest direction. Comparing these with the results from explosions (Figures 1b, c and 2b, c), the earthquake P coda has considerably more energy coming from the source region, probably because of the significantly longer source duration. Nevertheless, f-k based on residual seismograms (Figures 5d, e, f) and f-k power difference plots (Figures 5g, h, i) produce results for the secondary source that are remarkably similar to those from the two explosions (Figures 1 and 2).

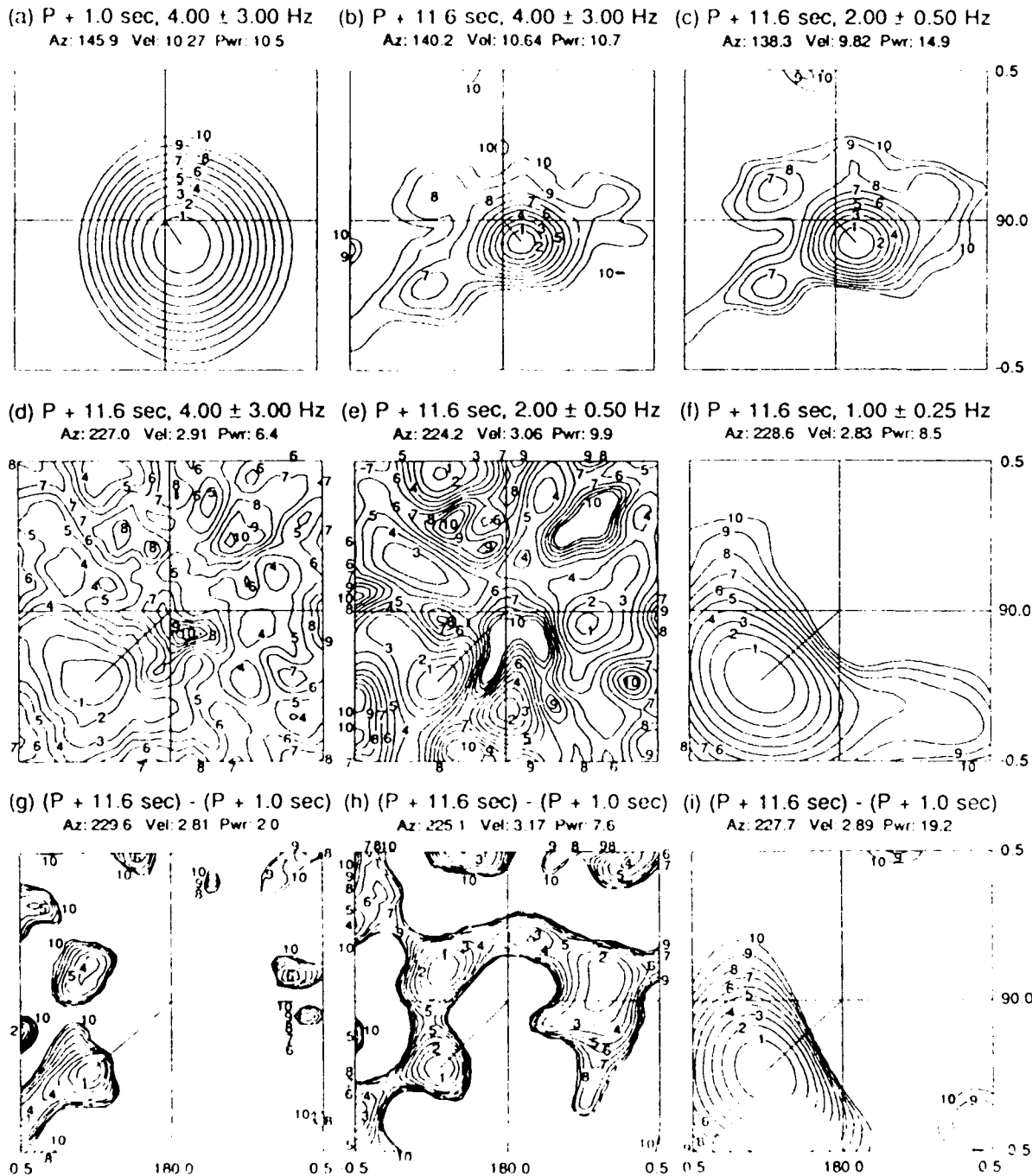


Figure 5. Similar to Figure 1 but derived from NORESS records of the Romanian earthquake of 1 August 1985. The low phase velocity arrival from the southwest direction appears as a secondary arrival in (b) and (c) but appears as the principal phase in all other later arrival windows.

F-K ANALYSIS OF DATA FROM RECIPROCAL ARRAYS

We also used f-k analysis to investigate near-source scattering by forming reciprocal arrays in which the roles of source and receiver are interchanged. Short-period records at a single station of seismic sources that are fairly similar and closely spaced may be used for this purpose. In order to simulate a reciprocal array, arrival times of the first peak in the direct P wavetrain from each explosion are used as reference points, and the traces are shifted on the basis of their predicted travel times to the recording station. Yucca Flat (NTS) explosions recorded at several stations at teleseismic distances were used to construct four reciprocal arrays, and the sources of secondary arrivals were examined. The locations of 39 shots used in each of the four reciprocal arrays used in this study are shown in Figure 6. Two of these arrays were derived from groups of 10 shots each recorded at the ASRO station MAJO; these have been designated as MAJO-North and MAJO-South. The center element NAO records of the NORSAR array for 15 shots provided another reciprocal array. Lastly, 18 records from a combination of the WWSSN stations TOL, PTO, and MAI, having nearly the same distance and back-azimuth to Yucca Flat were combined to form the fourth reciprocal array. The long dimensions of these four arrays vary from about 3 to 5 km. The seismic velocities in the Yucca Flat region are known to be considerably smaller than those in the shield region of NORESS. For this reason, 6.4 sec windows were used for the f-k analysis, and the maximum slowness was increased to 1.0 sec/km on all slowness plots.

Results from MAJO-North array are shown in Figure 7. Frequency-slowness plots, obtained with an incremental shift of 1 sec for three different frequency ranges, showed a prominent secondary arrival in the $P + 4$ sec window. Frequency-slowness plots of the initial

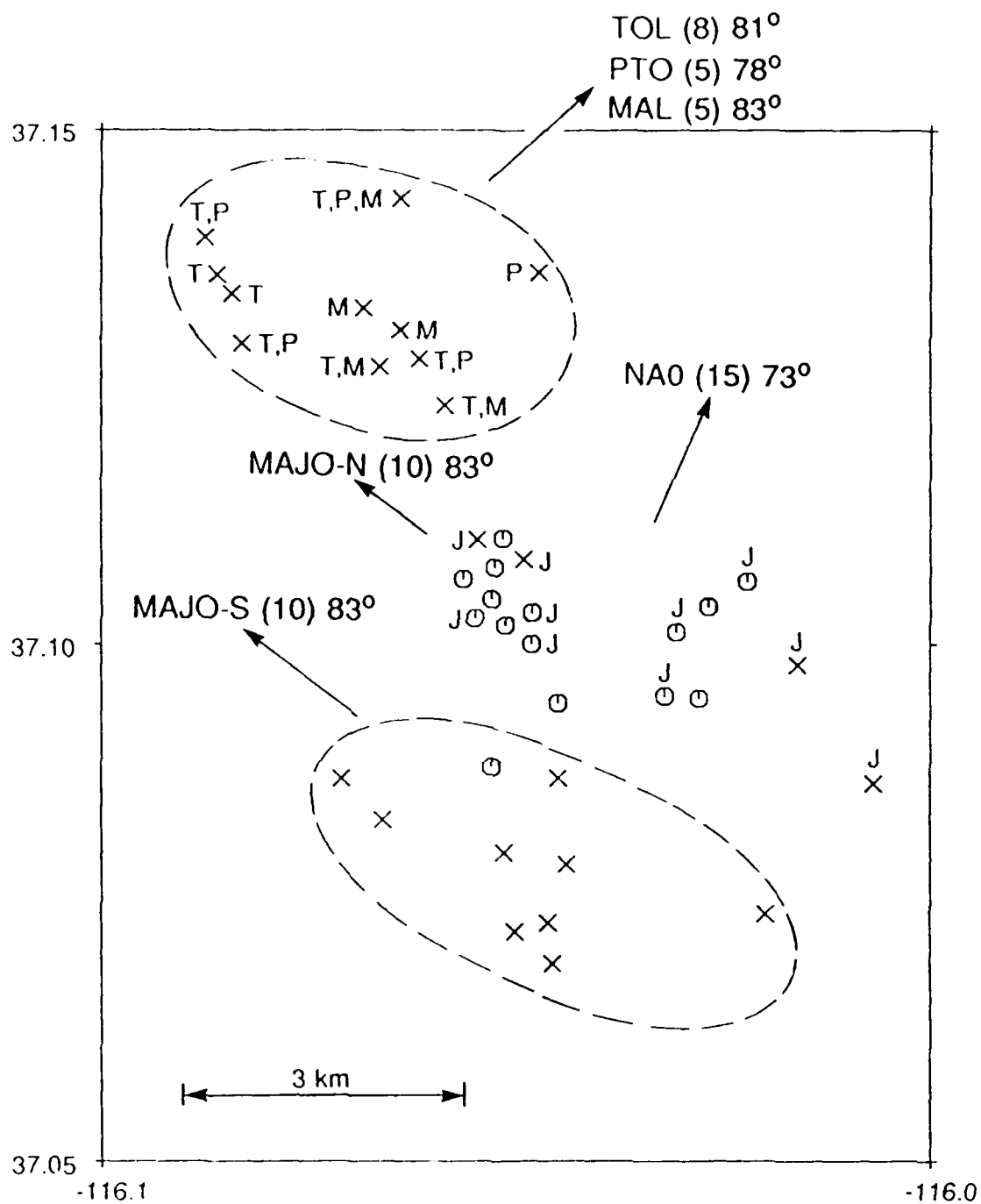


Figure 6. Locations of 39 Yucca Flat explosions used in forming four reciprocal arrays. (1) MAJO-North consists of 10 shots denoted by "J", (2) MAJO-South with 10 shots within the enclosed area, (3) NAO consists of 15 shots denoted by "o", and (4) TOL-PTO-MAL array consisting of 15 records of 11 shots. Arrows indicate azimuthal direction to each station or mean azimuth to group of stations. The first number for each array (in parentheses) indicates the number of shots and the second the distance in degrees.

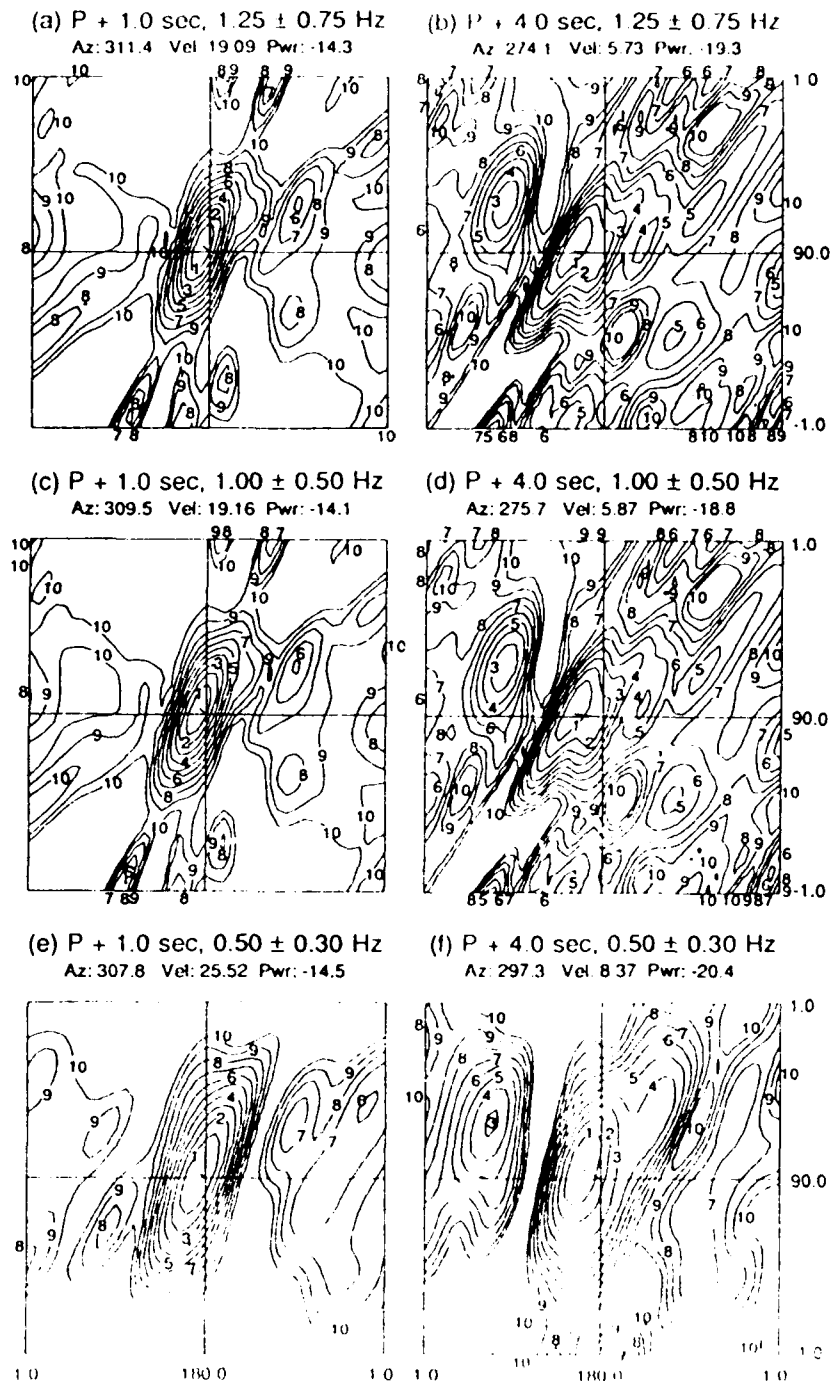


Figure 7. Similar to Figure 1 but derived from the reciprocal array MAJO-North. The maximum slowness value is 1.0 sec/km and results for three different frequency passbands are shown. The prominent secondary arrival in the P + 4 sec windows has a phase velocity of about 1.6 km/sec and azimuth of about 300° .

P (i.e., the $P + 1$ sec) window indicate that the dominant energy arrives close to the expected azimuth and phase velocity. However, unlike the results from the initial P window from NORESS (Figures 1a, 2a, 5a), there are several other secondary sources of energy. This contamination is at least in part due to the irregular distribution of shot locations and variations in their source functions. The prominent secondary arrival has a phase velocity of about 1.6 km/sec and arrives with an azimuth of about 300° .

Figure 8 shows results from MAJO-South array for the same three frequency ranges as in Figure 7. A prominent secondary arrival appears in the $P + 6$ sec windows, with phase velocity of about 1.6 and azimuth of about 260° . Results from the NAO array are shown in Figure 9. The secondary arrival appears best in the $P + 7$ sec window and has a phase velocity of about 1.8 km/sec and azimuth of about 270° . The array made by combining 18 records of 11 shots at 3 stations provided results shown in Figure 10. Here the $P + 7$ sec window shows a low phase velocity (about 2.3 km/sec) arrival as the primary phase, with azimuth of about 117° . This arrival in particular appears very similar in location and delay time to an arrival obtained by Lynnes and Lay (1989) from WWSSN and Canadian data using a semblance technique.

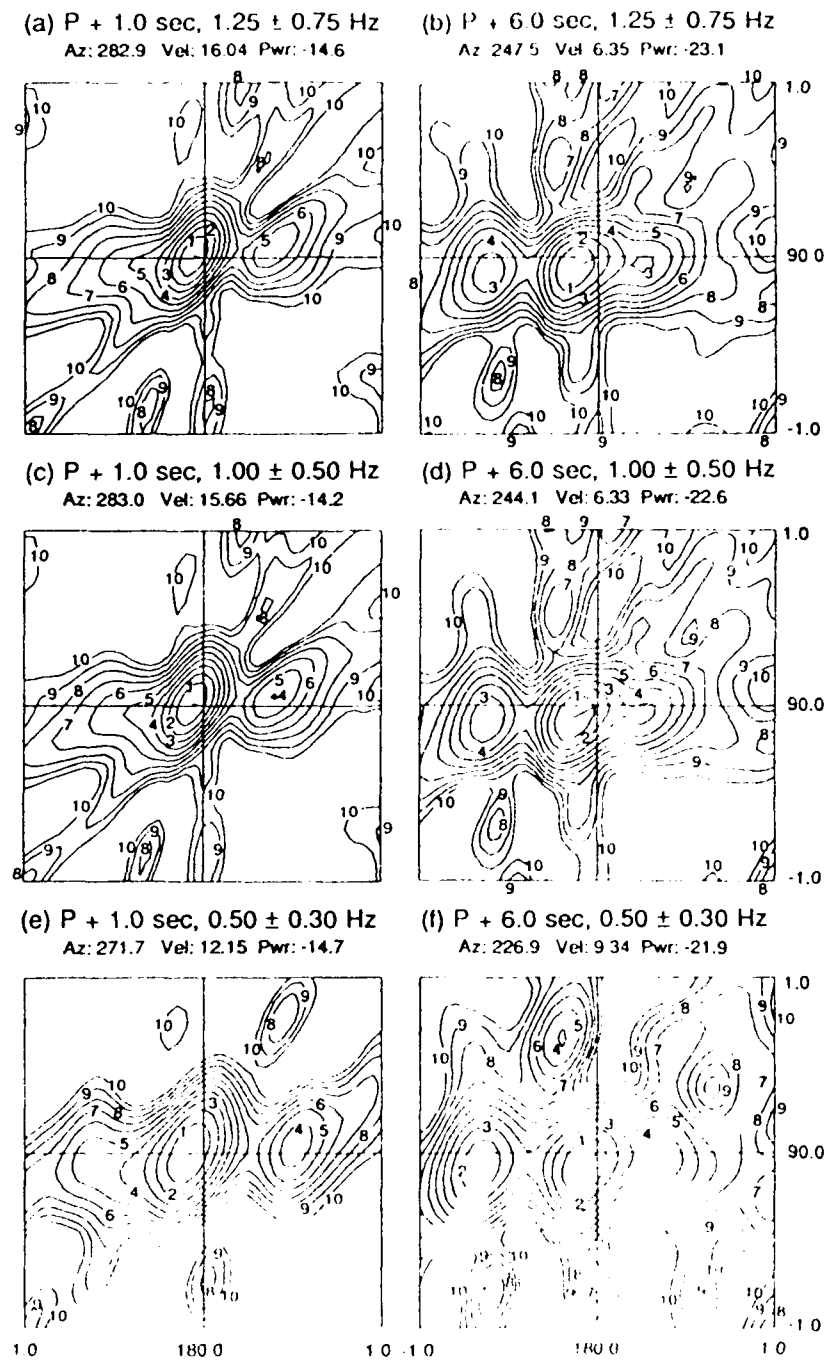


Figure 8. Similar to Figure 7 but derived from the reciprocal array MAJO-South. The prominent secondary arrival in the P + 6 sec window has a phase velocity of about 1.6 km/sec and azimuth of about 260° .

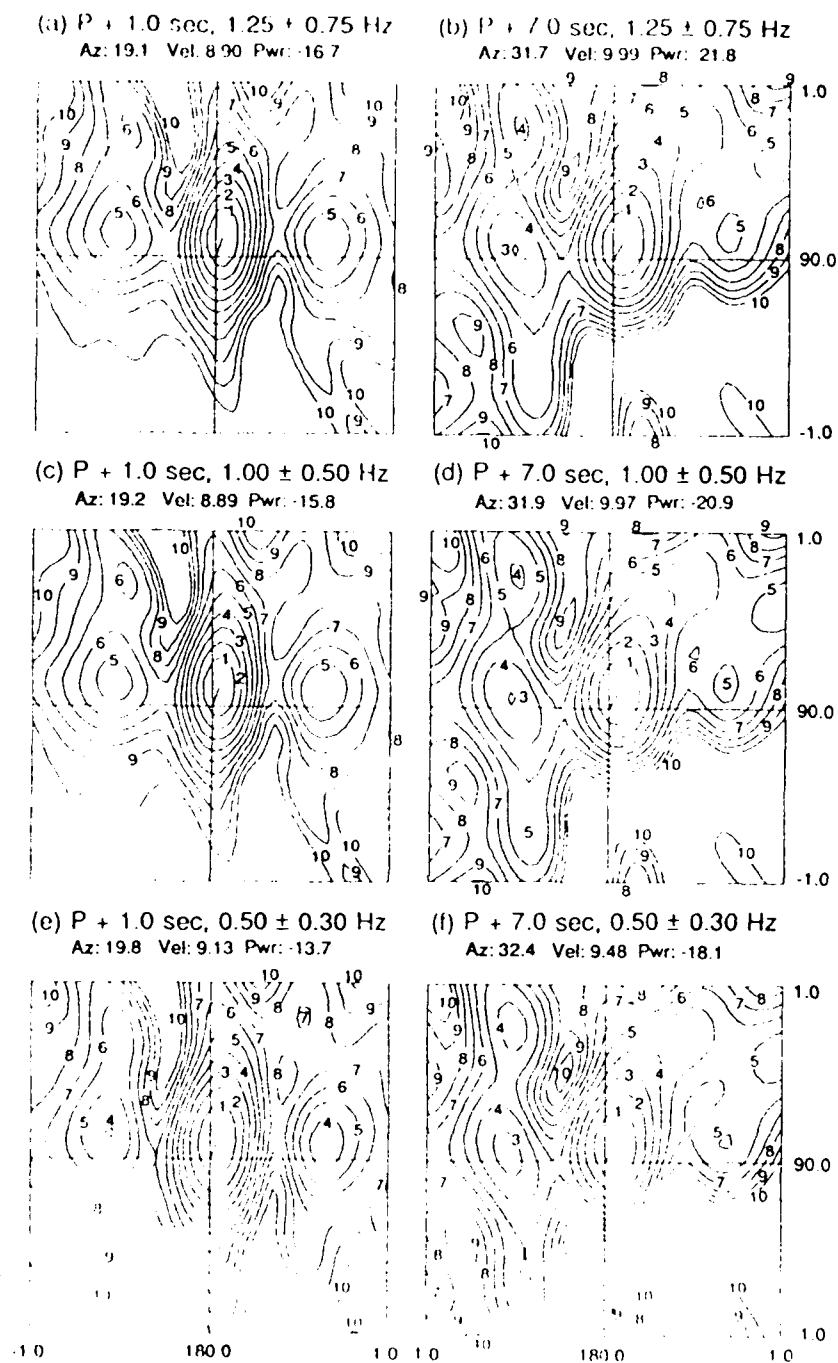


Figure 9. Similar to Figure 7 but derived from the reciprocal array NA0. The prominent secondary arrival in the $P + 7$ sec window has a phase velocity of about 1.8 km/sec and azimuth of about 270° .

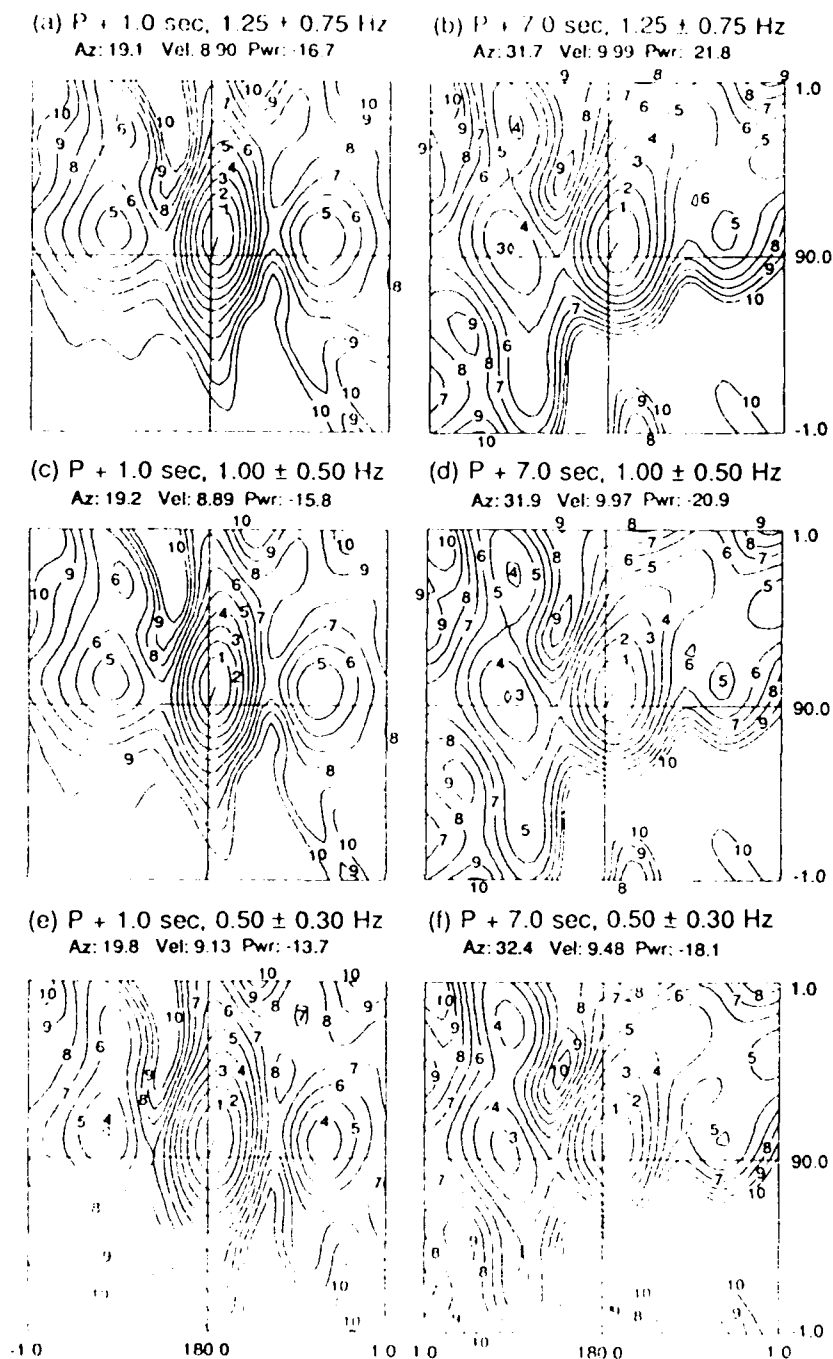


Figure 9. Similar to Figure 7 but derived from the reciprocal array NA0. The prominent secondary arrival in the $P + 7$ sec window has a phase velocity of about 1.8 km/sec and azimuth of about 270° .

DISCUSSION

F-k analysis of NORESS data from three seismic sources provide remarkably consistent results regarding the azimuthal direction and phase velocity of a secondary source lying southwest of the array, in the region of Lake Mjosa. The source-receiver azimuthal directions were such that the secondary arrival represents back-scattering for the Kazakh explosion and almost normal direction of scattering for the other two events. It seems therefore that the scattering observed in this study is not strongly dependent on the direction of the incident energy.

Considering the local structure of Yucca Flat as a basin containing low velocity tuffs and alluvium, Stead and Helmberger (1988) obtained synthetics that matched well with the observed waveforms and also explained the variation of coda levels with shot location found by Lynnes and Lay (1988). Gradual basin terminations were found to cause the greatest conversion of surface wave energy into teleseismic P arrivals, appearing a few seconds after P and pP . Our results from the four reciprocal arrays based on the use of Yucca Flat explosions also indicate secondary sources of energy, arriving a few seconds after the direct P . Considering the seismic velocities in this region (Hays and Murphy, 1971), the observed low phase velocity suggests these arrivals are due to Rayleigh waves. The azimuthal directions of the secondary sources in our study show large variations. Figure 11 shows Ferguson's (1981) model for Yucca Flat basin, derived from borehole data and gravity modeling, along with the Yucca Fault. The contours indicate depth to the Tertiary-Paleozoic contact in meters. Locations of the 39 shots are superposed on this map. The secondary arrival observed from the MAJO-North reciprocal array (Figure 7) is therefore likely to be due to Rayleigh $\rightarrow P$

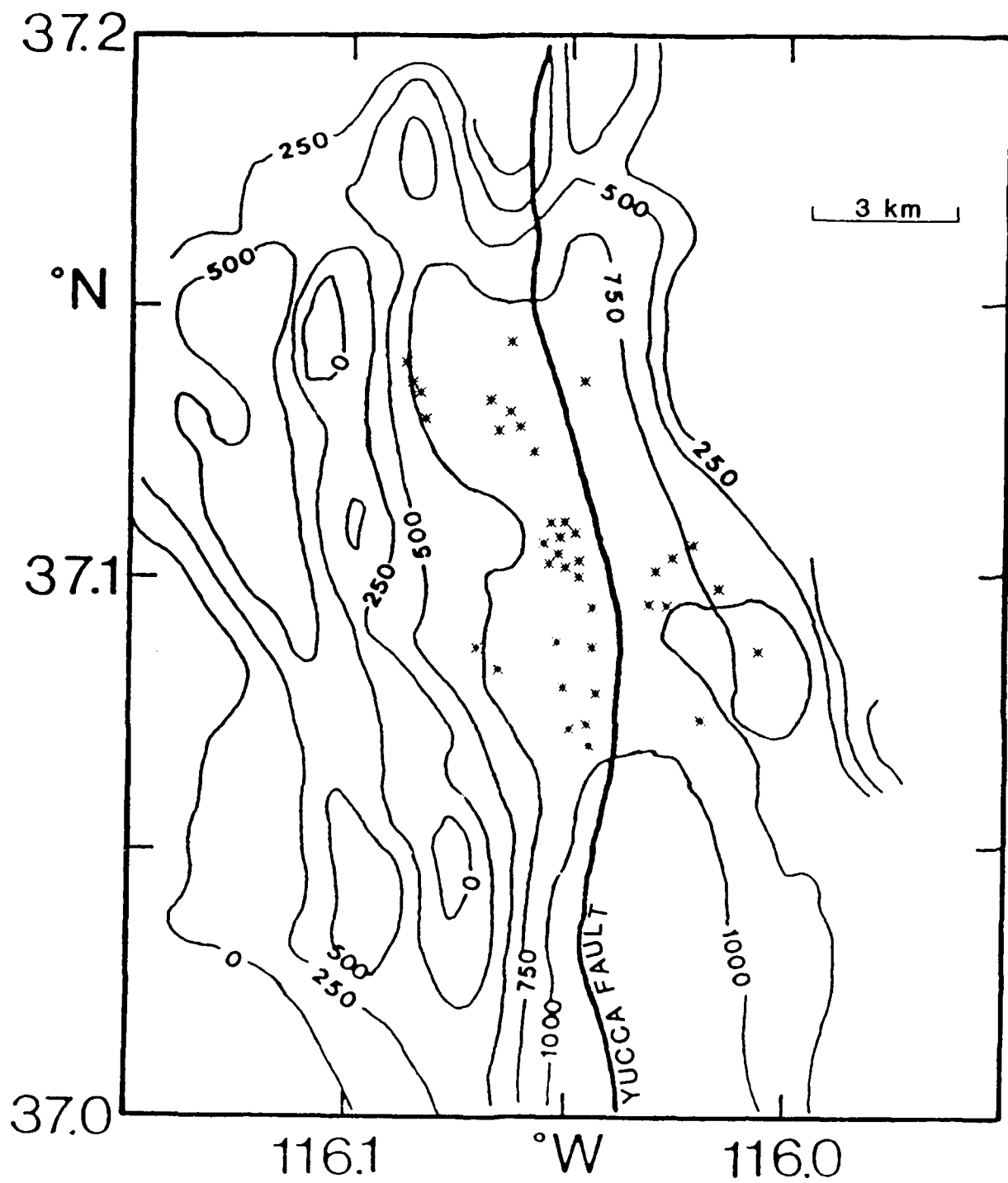


Figure 11. Yucca Fault basin showing depth in meters to Tertiary-Paleozoic contact and the locations of 39 explosions used in the study.

scattering near the northwestern basin boundary of the Yucca Valley. Similarly, our results from the other three reciprocal arrays (Figures 8, 9, and 10) probably indicate arrivals due to Rayleigh $\rightarrow P$ scattering near other basin boundaries of the Yucca Valley (e.g., Lynnes and Lay, 1989).

CONCLUSIONS

Deterministic locations of both near-receiver and near-source scattering are investigated by using several f-k techniques and polarization analyses. F-k spectral analyses of NORESS array data from both explosion and earthquake sources are used to identify and locate sources of local scattering. Residual seismograms and f-k power difference plots have been found to be useful in isolating the secondary source from the effects of the primary source. The most prominent and consistent scattered arrivals have been identified as low-velocity Rg due to the scattering of incident P in the region of Lake Mjosa with large topographical relief. Four reciprocal arrays formed by using single station records of closely spaced Yucca Flat explosions are used to investigate near-source scattering. Considering the geological structure of the Yucca Valley, the secondary sources of seismic energy appear to be due to $Rg \rightarrow P$ scattering near its basin boundaries.

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P.O. Box 830688
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Department of Geological Sciences
SNEE Hall
Ithaca, NY 14850

Dr. Rong-Song Jih
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

Prof. Lane R. Johnson
Seismographic Station
University of California
Berkeley, CA 94720

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Department of Geology & Geophysics
Boston College
Chestnut Hill, MA 02167

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Lamont-Doherty Geological Observatory
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Palisades, NY 10964

Dr. Christopher Lynnes
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

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University of California at Santa Barbara
Institute for Crustal Studies
Santa Barbara, CA 93106

Dr. Randolph Martin, III
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S-CUBED
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P.O. Box 1620
La Jolla, CA 92038-1620

Prof. William Menke
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Stephen Miller
SRI International
333 Ravenswood Avenue
Box AF 116
Menlo Park, CA 94025-3493

Prof. Bernard Minster
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Prof. Brian J. Mitchell
Department of Earth & Atmospheric Sciences
St. Louis University
St. Louis, MO 63156

Mr. Jack Murphy
S-CUBED, A Division of Maxwell Laboratory
11800 Sunrise Valley Drive
Suite 1212
Reston, VA 22091 (2 copies)

Dr. Bao Nguyen
GL/LWH
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Prof. John A. Orcutt
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Prof. Keith Priestley
University of Cambridge
Bullard Labs, Dept. of Earth Sciences
Madingley Rise, Madingley Rd.
Cambridge CB3 0EZ, ENGLAND

Prof. Paul G. Richards
L-210
Lawrence Livermore National Laboratory
Livermore, CA 94550

Dr. Wilmer Rivers
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314

Prof. Charles G. Sammis
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Prof. Christopher H. Scholz
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Prof. David G. Simpson
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Dr. Jeffrey Stevens
S-CUBED
A Division of Maxwell Laboratory
P.O. Box 1620
La Jolla, CA 92038-1620

Prof. Brian Stump
Institute for the Study of Earth & Man
Geophysical Laboratory
Southern Methodist University
Dallas, TX 75275

Prof. Jeremiah Sullivan
University of Illinois at Urbana-Champaign
Department of Physics
1110 West Green Street
Urbana, IL 61801

Prof. Clifford Thurber
University of Wisconsin-Madison
Department of Geology & Geophysics
1215 West Dayton Street
Madison, WI 53706

Prof. M. Nafi Toksoz
Earth Resources Lab
Massachusetts Institute of Technology
42 Carleton Street
Cambridge, MA 02142

Prof. John E. Vidale
University of California at Santa Cruz
Seismological Laboratory
Santa Cruz, CA 95064

Prof. Terry C. Wallace
Department of Geosciences
Building #77
University of Arizona
Tucson, AZ 85721

Dr. Raymond Willeman
GL/LWH
Hanscom AFB, MA 01731-5000

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Prof. Francis T. Wu
Department of Geological Sciences
State University of New York
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Dr. Monem Abdel-Gawad
Rockwell International Science Center
1049 Camino Dos Rios
Thousand Oaks, CA 91360

Prof. Keiiti Aki
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Prof. Shelton S. Alexander
Geosciences Department
403 Deike Building
The Pennsylvania State University
University Park, PA 16802

Dr. Kenneth Anderson
BBNSTC
Mail Stop 14/1B
Cambridge, MA 02238

Dr. Ralph Archuleta
Department of Geological Sciences
University of California at Santa Barbara
Santa Barbara, CA 93102

Dr. Thomas C. Bache, Jr.
Science Applications Int'l Corp.
10210 Campus Point Drive
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J. Barker
Department of Geological Sciences
State University of New York
at Binghamton
Vestal, NY 13901

Dr. T.J. Bennett
S-CUBED
A Division of Maxwell Laboratory
11800 Sunrise Valley Drive, Suite 1212
Reston, VA 22091

Mr. William J. Best
907 Westwood Drive
Vienna, VA 22180

Dr. N. Biswas
Geophysical Institute
University of Alaska
Fairbanks, AK 99701

Dr. G.A. Bollinger
Department of Geological Sciences
Virginia Polytechnical Institute
21044 Derring Hall
Blacksburg, VA 24061

Dr. Steven R. Bratt
Center for Seismic Studies
1300 North 17th St., Suite 1450
Arlington, VA 22209

Michael Browne
Teledyne Geotech
3401 Shiloh Road
Garland, TX 75041

Mr. Roy Burger
1221 Serry Road
Schenectady, NY 12309

Dr. Robert Burrige
Schlumberger-Doll Research Center
Old Quarry Road
Ridgefield, CT 06877

Dr. Jerry Carter
Rondout Associates
P.O. Box 224
Stone Ridge, NY 12484

Dr. W. Winston Chan
Teledyne Geotech
314 Montgomery Street
Alexandria, VA 22314-1581

Dr. Theodore Cherry
Science Horizons, Inc.
710 Encinitas Blvd., Suite 200
Encinitas, CA 92024 (2 copies)

Prof. Jon F. Claerbout
Department of Geophysics
Stanford University
Stanford, CA 94305

Prof. Robert W. Clayton
Seismological Laboratory
Division of Geological & Planetary Sciences
California Institute of Technology
Pasadena, CA 91125

Prof. F. A. Dahlen
Geological and Geophysical Sciences
Princeton University
Princeton, NJ 08544-0636

Dr. Jeffrey W. Given
Sierra Geophysics
11255 Kirkland Way
Kirkland, WA 98033

Prof. Adam Dziewonski
Hoffman Laboratory
Harvard University
20 Oxford St
Cambridge, MA 02138

Prof. Stephen Grand
University of Texas at Austin
Department of Geological Sciences
Austin, TX 78713-7909

Prof. John Ebel
Department of Geology & Geophysics
Boston College
Chestnut Hill, MA 02167

Prof. Roy Greenfield
Geosciences Department
403 Deike Building
The Pennsylvania State University
University Park, PA 16802

Eric Fielding
SNEE Hall
INSTOC
Cornell University
Ithaca, NY 14853

Dan N. Hagedorn
Battelle
Pacific Northwest Laboratories
Battelle Boulevard
Richland, WA 99352

Prof. Donald Forsyth
Department of Geological Sciences
Brown University
Providence, RI 02912

Kevin Hutchenson
Department of Earth Sciences
St. Louis University
3507 Laclede
St. Louis, MO 63103

Dr. Cliff Frolich
Institute of Geophysics
8701 North Mopac
Austin, TX 78759

Prof. Thomas H. Jordan
Department of Earth, Atmospheric
and Planetary Sciences
Massachusetts Institute of Technology
Cambridge, MA 02139

Prof. Art Frankel
Mail Stop 922
Geological Survey
790 National Center
Reston, VA 22092

Robert C. Kemerait
ENSCO, Inc.
445 Pineda Court
Melbourne, FL 32940

Dr. Anthony Gangi
Texas A&M University
Department of Geophysics
College Station, TX 77843

William Kikendall
Teledyne Geotech
3401 Shiloh Road
Garland, TX 75041

Dr. Freeman Gilbert
Inst. of Geophysics & Planetary Physics
University of California, San Diego
P.O. Box 109
La Jolla, CA 92037

Prof. Leon Knopoff
University of California
Institute of Geophysics & Planetary Physics
Los Angeles, CA 90024

Mr. Edward Giller
Pacific Sierra Research Corp.
1401 Wilson Boulevard
Arlington, VA 22209

Prof. L. Timothy Long
School of Geophysical Sciences
Georgia Institute of Technology
Atlanta, GA 30332

Prof. Art McGarr
Mail Stop 977
Geological Survey
345 Middlefield Rd.
Menlo Park, CA 94025

Dr. George Mellman
Sierra Geophysics
11255 Kirkland Way
Kirkland, WA 98033

Prof. John Nabelek
College of Oceanography
Oregon State University
Corvallis, OR 97331

Prof. Geza Nagy
University of California, San Diego
Department of Ames, M.S. B-010
La Jolla, CA 92093

Prof. Amos Nur
Department of Geophysics
Stanford University
Stanford, CA 94305

Prof. Jack Oliver
Department of Geology
Cornell University
Ithaca, NY 14850

Prof. Robert Phinney
Geological & Geophysical Sciences
Princeton University
Princeton, NJ 08544-0636

Dr. Paul Pomeroy
Rondout Associates
P.O. Box 224
Stone Ridge, NY 12484

Dr. Jay Pulli
RADIX System, Inc.
2 Taft Court, Suite 203
Rockville, MD 20850

Dr. Norton Rimer
S-CUBED
A Division of Maxwell Laboratory
P.O. Box 1620
La Jolla, CA 92038-1620

Prof. Larry J. Ruff
Department of Geological Sciences
1006 C.C. Little Building
University of Michigan
Ann Arbor, MI 48109-1063

Dr. Richard Sailor
TASC Inc.
55 Walkers Brook Drive
Reading, MA 01867

Thomas J. Sereno, Jr.
Science Application Int'l Corp.
10210 Campus Point Drive
San Diego, CA 92121

John Sherwin
Teledyne Geotech
3401 Shiloh Road
Garland, TX 75041

Prof. Robert Smith
Department of Geophysics
University of Utah
1400 East 2nd South
Salt Lake City, UT 84112

Prof. S. W. Smith
Geophysics Program
University of Washington
Seattle, WA 98195

Dr. Stewart Smith
IRIS Inc.
1616 North Fort Myer Drive
Suite 1440
Arlington, VA 22209

Dr. George Sutton
Rondout Associates
P.O. Box 224
Stone Ridge, NY 12484

Prof. L. Sykes
Lamont-Doherty Geological Observatory
of Columbia University
Palisades, NY 10964

Prof. Pradeep Talwani
Department of Geological Sciences
University of South Carolina
Columbia, SC 29208

Prof. Ta-liang Teng
Center for Earth Sciences
University of Southern California
University Park
Los Angeles, CA 90089-0741

Dr. R.B. Tittmann
Rockwell International Science Center
1049 Camino Dos Rios
P.O. Box 1085
Thousand Oaks, CA 91360

Dr. Gregory van der Vink
IRIS, Inc.
1616 North Fort Myer Drive
Suite 1440
Arlington, VA 22209

Professor Daniel Walker
University of Hawaii
Institute of Geophysics
Honolulu, HI 96822

William R. Walter
Seismological Laboratory
University of Nevada
Reno, NV 89557

Dr. Gregory Wojcik
Weidlinger Associates
4410 El Camino Real
Suite 110
Los Altos, CA 94022

Prof. John H. Woodhouse
Hoffman Laboratory
Harvard University
20 Oxford St.
Cambridge, MA 02138

Dr. Gregory B. Young
ENSCO, Inc.
5400 Port Royal Road
Springfield, VA 22151-2388

GOVERNMENT

Dr. Ralph Alewine III
DARPA/NMRO
1400 Wilson Boulevard
Arlington, VA 22209-2308

Paul Johnson
ESS-4, Mail Stop J979
Los Alamos National Laboratory
Los Alamos, NM 87545

Mr. James C. Battis
GL/LWH
Hanscom AFB, MA 01731-5000

Janet Johnston
GL/LWH
Hanscom AFB, MA 01731-5000

Dr. Robert Blandford
DARPA/NMRO
1400 Wilson Boulevard
Arlington, VA 22209-2308

Dr. Katharine Kadinsky-Cade
GL/LWH
Hanscom AFB, MA 01731-5000

Eric Chael
Division 9241
Sandia Laboratory
Albuquerque, NM 87185

Ms. Ann Kerr
IGPP, A-025
Scripps Institute of Oceanography
University of California, San Diego
La Jolla, CA 92093

Dr. John J. Cipar
GL/LWH
Hanscom AFB, MA 01731-5000

Dr. Max Koontz
US Dept of Energy/DP 5
Forrestal Building
1000 Independence Avenue
Washington, DC 20585

Mr. Jeff Duncan
Office of Congressman Markey
2133 Rayburn House Bldg.
Washington, DC 20515

Dr. W.H.K. Lee
Office of Earthquakes, Volcanoes,
& Engineering
345 Middlefield Road
Menlo Park, CA 94025

Dr. Jack Evernden
USGS - Earthquake Studies
345 Middlefield Road
Menlo Park, CA 94025

Dr. William Leith
U.S. Geological Survey
Mail Stop 928
Reston, VA 22092

Art Frankel
USGS
922 National Center
Reston, VA 22092

Dr. Richard Lewis
Director, Earthquake Engineering & Geophysics
U.S. Army Corps of Engineers
Box 631
Vicksburg, MS 39180

Dr. T. Hanks
USGS
Nat'l Earthquake Research Center
345 Middlefield Road
Menlo Park, CA 94025

James F. Lewkowicz
GL/LWH
Hanscom AFB, MA 01731-5000

Dr. James Hannon
Lawrence Livermore Nat'l Laboratory
P.O. Box 808
Livermore, CA 94550

Mr. Alfred Lieberman
ACDA/VI-OA'State Department Bldg
Room 5726
320 - 21st Street, NW
Washington, DC 20451

Stephen Mangino
GL/LWH
Hanscom AFB, MA 01731-5000

Dr. Frank F. Pilotte
HQ AFTAC/TT
Patrick AFB, FL 32925-6001

Dr. Robert Masse
Box 25046, Mail Stop 967
Denver Federal Center
Denver, CO 80225

Katie Poley
CIA-OSWR/NED
Washington, DC 20505

Art McGarr
U.S. Geological Survey, MS-977
345 Middlefield Road
Menlo Park, CA 94025

Mr. Jack Rachlin
U.S. Geological Survey
Geology, Rm 3 C136
Mail Stop 928 National Center
Reston, VA 22092

Richard Morrow
ACDA/VI, Room 5741
320 21st Street N.W.
Washington, DC 20451

Dr. Robert Reinke
WL/NTESG
Kirtland AFB, NM 87117-6008

Dr. Keith K. Nakanishi
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Dr. Byron Ristvet
HQ DNA, Nevada Operations Office
Attn: NVCG
P.O. Box 98539
Las Vegas, NV 89193

Dr. Carl Newton
Los Alamos National Laboratory
P.O. Box 1663
Mail Stop C335, Group ESS-3
Los Alamos, NM 87545

Dr. George Rothe
HQ AFTAC/TGR
Patrick AFB, FL 32925-6001

Dr. Kenneth H. Olsen
Los Alamos Scientific Laboratory
P.O. Box 1663
Mail Stop C335, Group ESS-3
Los Alamos, NM 87545

Dr. Alan S. Ryall, Jr.
DARPA/NMRO
1400 Wilson Boulevard
Arlington, VA 22209-2308

Howard J. Patton
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Dr. Michael Shore
Defense Nuclear Agency/SPSS
6801 Telegraph Road
Alexandria, VA 22310

Mr. Chris Paine
Office of Senator Kennedy
SR 315
United States Senate
Washington, DC 20510

Donald L. Springer
Lawrence Livermore National Laboratory
P.O. Box 808, L-205
Livermore, CA 94550

Colonel Jerry J. Perrizo
AFOSR/NP, Building 410
Bolling AFB
Washington, DC 20332-6448

Mr. Charles L. Taylor
GL/LWG
Hanscom AFB, MA 01731-5000

Dr. Thomas Weaver
Los Alamos National Laboratory
P.O. Box 1663, Mail Stop C335
Los Alamos, NM 87545

DARPA/PM
1400 Wilson Boulevard
Arlington, VA 22209

J.J. Zucca
Lawrence Livermore National Laboratory
Box 808
Livermore, CA 94550

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DDR & E
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1400 Wilson Boulevard
Arlington, VA 22209

Geophysics Laboratory
Attn: XO
Hanscom AFB, MA 01731-5000

Geophysics Laboratory
Attn: LW
Hanscom AFB, MA 01731-5000

CONTRACTORS (Foreign)

Dr. Ramon Cabre, S.J.
Observatorio San Calixto
Casilla 5939
La Paz, Bolivia

• Prof. Hans-Peter Harjes
Institute for Geophysik
Ruhr University/Bochum
• P.O. Box 102148
4630 Bochum 1, FRG

Prof. Eystein Husebye
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Prof. Brian L.N. Kennett
Research School of Earth Sciences
Institute of Advanced Studies
G.P.O. Box 4
Canberra 2601, AUSTRALIA

Dr. Bernard Massinon
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE (2 Copies)

Dr. Pierre Mecheler
Societe Radiomana
27 rue Claude Bernard
75005 Paris, FRANCE

Dr. Svein Mykkeltveit
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

FOREIGN (Others)

Dr. Peter Basham
Earth Physics Branch
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Eduard Berg
Institute of Geophysics
University of Hawaii
Honolulu, HI 96822

Dr. Michel Bouchon
I.R.I.G.M.-B.P. 68
38402 St. Martin D'Heres
Cedex, FRANCE

Dr. Hilmar Bungum
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Dr. Michel Campillo
Observatoire de Grenoble
I.R.I.G.M.-B.P. 53
38041 Grenoble, FRANCE

Dr. Kin Yip Chun
Geophysics Division
Physics Department
University of Toronto
Ontario, CANADA M5S 1A7

Dr. Alan Douglas
Ministry of Defense
Blacknest, Brimpton
Reading RG7-4RS, UNITED KINGDOM

Dr. Roger Hansen
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Dr. Manfred Henger
Federal Institute for Geosciences & Nat'l Res.
Postfach 510153
D-3000 Hanover 51, FRG

Ms. Eva Johannisson
Senior Research Officer
National Defense Research Inst.
P.O. Box 27322
S-102 54 Stockholm, SWEDEN

Dr. Fekadu Kebede
Seismological Section
Box 12019
S-750 Uppsala, SWEDEN

Dr. Tormod Kvaerna
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Dr. Peter Marshal
Procurement Executive
Ministry of Defense
Blacknest, Brimpton
Reading FG7-4RS, UNITED KINGDOM

Prof. Ari Ben-Menahem
Department of Applied Mathematics
Weizman Institute of Science
Rehovot, ISRAEL 951729

Dr. Robert North
Geophysics Division
Geological Survey of Canada
1 Observatory Crescent
Ottawa, Ontario, CANADA K1A 0Y3

Dr. Frode Ringdal
NTNF/NORSAR
P.O. Box 51
N-2007 Kjeller, NORWAY

Dr. Jorg Schlittenhardt
Federal Institute for Geosciences & Nat'l Res.
Postfach 510153
D-3000 Hannover 51, FEDERAL REPUBLIC OF
GERMANY